# Search for Second-Generation Scalar Leptoquarks in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV

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Results on a search for pair production of second generation scalar leptoquark in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV are reported. The data analyzed were collected by the CDF detector during the 2002-2003 Tevatron Run II and correspond to an integrated luminosity of 198 pb$^{-1}$. Leptoquarks (LQ) are sought through their decay into (charged) leptons and quarks, with final state signatures represented by two muons and jets and one muon, large transverse missing energy and jets. We observe no evidence for $LQ$ production and derive 95% C.L. upper limits on the $LQ$ production cross sections as well as lower limits on their mass as a function of $\beta$, where $\beta$ is the branching fraction for $LQ \rightarrow \mu q$.

The symmetry between leptons and quarks present in the standard model (SM) of particle physics, has lead to the theoretical speculation that a more foundamental force could operate at energy scales larger than the electroweak symmetry breaking scale, allowing for quark to lepton transitions, mediated by new gauge bosons. Theories like grand unification or R-parity violating supersymmetric models introduce the idea of quark to lepton transitions[1]. Whenever quarks and leptons are allowed to couple directly to each other, new bosons carrying

both lepton and baryon quantum numbers can also exist. They are called leptoquark (LQ)[2], they can have spin 0 (scalar LQ) or 1 (vector LQ),are color-triplet particles, and can either be produced singly or in pairs. Most of the other characteristics, such as weak ispospin, electric charge and the coupling $\lambda$ to lepton and quark are model dependent[3]. Their masses are not predicted. To accomodate experimental constraints on flavor changing neutral currents, LQ are assumed to couple to fermions of the same generation[3, 4]. While first generation LQ have been extensively searched for at $e-p$, $e^+e^-$ and $p\bar{p}$ colliders, via single and pair production, and strong limits on their production cross section and mass have been set[6, 7], second and third generation LQ are detectable via pair production at hadronic colliders and can be singly produced at $e^+e^-$ machines. Indeed upper limits on second generation LQ production cross section and lower limits on their masses exist from LEP[8] and the Tevatron Run I[5, 9], but they are usually weaker than the ones for first generation LQ. In this paper we present new results on a search for second generation LQ pair production in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV. Assuming two different values for the LQ branching fraction $\beta$ to muon and quark, we consider the following final state signatures: both LQ decaying into muons of opposite charge and quarks ($\beta = 1$), and one of the LQ decaying into a muon and a quark and the other into a neutrino and a quark ($\beta = 0.5$). Since we do not observe evidence for LQ production, we set an upper limit on the production cross section times branching fraction (Br) where Br = $\beta^2$ or Br = $2\beta(1-\beta)$. These results are then combined with the one from a search for scalar LQ pairs decaying into $\nu\nu qq$, resulting in jets and missing transverse energy topology[10]. In this way we can express our limits as a continous function of the parameter $\beta$.

CDF is a general–purpose detector built to study the physics of $p\bar{p}$ collisions at the Tevatron accelerator at Fermilab and it is described in detail elsewhere [11]. We use a cylindrical coordinate system around the beampipe in which $\theta$ is the polar angle, $\phi$ is the azimuthal angle and $\eta = -\ln(\tan(\frac{\theta}{2}))$. The transverse energy is defined as $E_T = E\sin\theta$ and the transverse momentum is defined as $P_T = P\sin\theta$, where $E$ is the energy measured by the calorimeter and $P$ the momentum measured by the tracking system. The vector $\vec{\rlap{/}E}_T$ is equal to $-\Sigma E_T^i \bar{n}_i$ where $\bar{n}_i$ is a unit vector that points from the interaction vertex to the $i$th calorimeter tower in the transverse plane. Its magnitude, $\rlap{/}E_T$, is called transverse missing energy. $\rlap{/}E_T$ is corrected following the correction of jet energies, and if muons are identified in the event, $\rlap{/}E_T$ is corrected for the muon momenta.

The data used in the analysis were collected during the 2002-2003 Tevatron Run II. The integrated luminosity for this data sample is $198 \pm 12$ pb$^{-1}$. Events are selected online by requiring track segments ("stubs") reconstructed in the muon chambers and matched to individual tracks reconstructed in the central tracker (high $P_T$ muon trigger). The efficiency of the trigger combinations used in the $\mu\mu jj$ and $\mu\nu jj$ analyses, measured using $Z \to \mu^+\mu^-$ data[12, 13], is $\sim 90\%$, varying from about 87% to 95% depending on the type of muon chamber used to detect the candidate muon. Muons are selected as "tight" or "loose" (this second category being used in the $\mu\mu$ analysis only). A tight muon requires a reconstructed track segment in the muon chambers with positions well matched to the extrapolation of a single track, while a loose muon is the one selected by requiring only one isolated track. In both cases the energy deposition in the calorimeters must be consistent with that of a minimum-ionizing particle. We apply a cut on the $\chi^2$ of the track fit to eliminate kaons and pions which have decayed in flight. The identification efficiency for muons has also been measured using data[12, 13] and is approximately 90%, going from 89% to 95% for different types of detector and selection used to identify the candidate muon. The coordinate of the lepton (also assumed to be the event coordinate) along the beamline must fall within 60 cm of the center of the detector ($z_{vertex}$ cut) to ensure a good energy measurement in the calorimeter. This cut has an efficiency of $(95 \pm 0.1(stat) \pm 0.5(sys))\%$, and is determined from studies of minimum bias events. The efficiencies of the identification cuts, the trigger selection and the vertex cut, measured using data are taken into account by using scale factors between data and Monte Carlo events. Jets are reconstructed using a cone of fixed radius $R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} = 0.7$ and for these analyses are required to be in the $|\eta| < 2.0$ range. Jets are calibrated as a function of $\eta$ and $E_T$ and their energy is corrected to the parton level[14]. Neutrinos produce missing transverse energy, $\rlap{/}E_T$, which is measured by balancing the calorimeter energy in the transverse plane. The muon sample is heavily contaminated by events produced by cosmic rays interactions with the detector. Since these events do not originate from a common interaction vertex, the timing capability of the Central Outer Tracker (COT) is used to reject events with two muon tracks, one of which travels toward the beam pipe. We also require that the muon track passes close to the beam line, within distances less than 0.02 cm (0.2 cm) for tracks with (without) silicon hits. In the analyses we are describing, the signal selection criteria are set according to the kinematic distribution (e.g. $p_T$ of the muons and $E_T$ of the jets) of decay products determined from Monte Carlo studies, optimized to eliminate background with a minimal loss of signal events[15].

In the dimuon + jets topology, from the inclusive muon triggers dataset we select events with two reconstructed isolated muons with $P_T > 25$ GeV/c. The first muon is required to be tight, i.e. to have a stub associated to a track, while the second one can be without a stub ("stubless"). Events are further selected if there are at least two jets with $E_T > 30$ and 15 GeV respectively. In

the search in the muon, neutrino and two jets topology, we select events with one reconstructed tight muon with $P_T > 25$ GeV/c. We veto events with a second loose or tight muon to be orthogonal to the previous selection. We then accept events where there is large missing transverse energy, $\not{E}_T > 60$ GeV and at least two jets with $E_T > 30$ GeV.

The above datasets are composed predominantly of events coming from QCD production of $Z/W$ bosons in association with jets and $t\bar{t}$ production (where one or both the $W$'s from top decay into muon and neutrino). To reduce these backgrounds we apply several cuts which depend on the final state topology.

1) $\mu\mu$ analysis:

i) veto of events whose reconstructed dilepton mass falls in the window $76 < m_{\mu\mu} < 110$ GeV/c$^2$ to remove the $Z$ + jets contribution and $m_{\mu\mu} < 15$ GeV/c$^2$ to avoid contamination from $J/\Psi$ and $\Upsilon$ production; ii) $E_T(j_1) + E_T(j_2) > 85$ GeV and $E_T(e_1) + E_T(e_2) > 85$ GeV, iii) $\sqrt{((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)} > 200$ GeV. The effect of the last two cuts is shown in Fig. 1, where SM background is compared to a $LQ$ signal for $M_{LQ} = 220$ GeV/c$^2$.
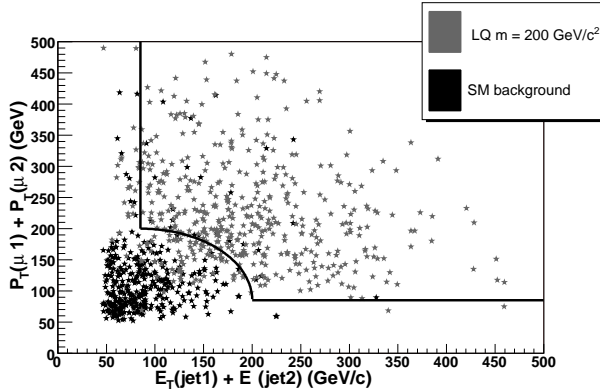


FIG. 1: Graphical representation of the last two topological cuts applied in the $\mu\mu jj$ analysis as observed on MC events. The discrimination between SM background and $LQ$ signal is evident.

2) $\mu\nu$ analysis:

i)$\Delta\phi(\not{E}_T - jet) > 5°$ to veto events where the transverse missing energy is mis-measured due to a mismeasure of the jet energy, and $\Delta\phi(\not{E}_T - \mu) < 175°$ to ensure that that the missing energy does not come from mis-measurement of the muon momentum. ii)$E_T(j_1) + E_T(j_2) > 80$ GeV, iii)$M_T(\mu\nu) > 120$ GeV/c$^2$ to reduce the W + 2 jets background; iv) a mass dependent cut consisting in selecting events falling in mass windows defined around several LQ masses. We require that the reconstructed mass combinations of the jets, muon and $\not{E}_T$ be consistent with those reconstructed from the LQ Monte Carlo. The ambiguity of the jet assignments allows for two different sets of reconstructed LQ pairs in each event,

from which we build lineshapes of mass distributions by matching the reconstructed objects to the generator level objects. The lineshapes are then used with the following selection: $|M(\mu, j_1) - M_{LQ}| < 2\sigma_1$ or $|M(\mu, j_2) - M_{LQ}| < 2\sigma_2$, and $M_T(\not{E}_T, j_1) > T_1^{min}$ or $M_T(\not{E}_T, j_2) > T_2^{min}$, where $M_{LQ}$ is the mean of the reconstructed LQ distribution and $\sigma_{1,2}$ are the width parameterizations. $M(\mu, j_{1,2})$ are the reconstructed muon-jet invariant masses while $M_T(\not{E}_T, j_{1,2})$ are the reconstructed neutrino-jet transverse invariant masses. For the transverse mass distributions, we have chosen a mass-dependent lower cut denoted by $T_{1,2}^{min}$: $T_1^{min} = 20 + (M_{LQ} - 120)$ GeV/c$^2$, and $T_2^{min} = 20 + (M_{LQ} - 120)/2$ GeV/c$^2$. In Fig. 2 we plot the mass distributions of the selected events (before the mass limit cut) compared to the signal distribution for $m_{LQ} = 180$ GeV/c$^2$.
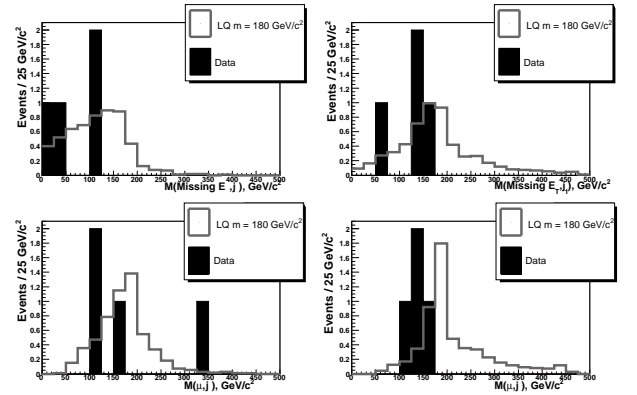


FIG. 2: Final mass distributions (see text) of the surviving events before the mass limit cut compared to the signal distribution for $M_{LQ} = 180$ GeV/c$^2$.

We study the properties of the physics backgrounds by generating events corresponding to $Z/W$ + 2 jets with ALPGEN[16] + HERWIG [17] (to perform parton showering) and $t\bar{t}$ with PYTHIA [18]. A complete simulation of the CDF II detector based on GEANT[19] and full event reconstruction is then performed. To normalize the number of simulated events to data we use the theoretical cross sections for $t\bar{t}$ from [20] and for $\gamma/Z \to \mu\mu$ + 2 jets from [21]. The background arising from multijet events, where a jet is mismeasured as a muon or where the muon comes from pion decay (QCD/fake), is evaluated using data. In the $\mu\mu jj$ analysis we examine the data for same-sign events (events with two muons of the same charge) remaining after each kinematical cut. We estimate the background contribution to be twice the number of same sign events, in the assumption that there is no evidence of LQ signal in these type of events (the LQ pair have opposite charge, giving rise to two opposite charge muons). In the $\mu\nu jj$ analysis the contribution from the QCD/fakes background is estimated by examining the phase space of the $\not{E}_T$ vs the muon fractional isolation for data events in which the muon isolation requirement is not enforced.

Here the muon fractional isolation is defined as the ratio between the calorimetric energy not associated with the lepton in a cone of $\Delta R = 0.4$ around the lepton and the energy of the lepton. The following assumptions are made: since jets are produced in association with other particles, the isolation fraction of a jet will generally be larger than the one corresponding to a muon; there is no correlation between the isolation of the muon and $\not{E}_T$, and in the region where the $\not{E}_T$ is small and the isolation of the muon is large the LQ contribution is expected to be negligible (background-dominated region). With these assumptions, from the ratio of the number of events

in the background-dominated regions we can extrapolate the contribution in the signal region. Other backgrounds from $b\bar{b}$, $Z \rightarrow \tau\bar{\tau}$, $WW$ are negligible due to the muon isolation and large muon and jet transverse energy requirements. In the $\mu\mu$ channel the expected number of $Z + 2$ jets events is $1.7 \pm 0.1$. The expected number of $t\bar{t}$ events is $0.22 \pm 0.03$ events. We estimate $1 \pm 1$ fake events The overall background estimate is: $3 \pm 1$ events. In the $\mu\nu$ channel, the number of events in each mass region, compared with the background expectations is reported in Table I.

TABLE I: Number of events surviving all cuts in the muon, missing energy and jets topology, compared with background expectations, as a function of the LQ mass (in $GeV/c^2$). Errors on the expectations are both statistical and systematic.

| Mass | 140 | 160 | 180 | 200 | 220 |
|------|-----|-----|-----|-----|-----|
| Wjj | $0.9 \pm 0.1$ | $1.4 \pm 0.1$ | $1.4 \pm 0.1$ | $1.6 \pm 0.1$ | $1.6 \pm 0.1$ |
| top | $1.7 \pm 0.2$ | $1.8 \pm 0.2$ | $1.4 \pm 0.2$ | $1.0 \pm 0.2$ | $0.8 \pm 0.2$ |
| Zjj | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ |
| multijets | $0.3 \pm 0.3$ | $0.3 \pm 0.3$ | $0.3 \pm 0.3$ | $0.3 \pm 0.3$ | $0.3 \pm 0.3$ |
| Total | $3.1 \pm 0.3$ | $3.7 \pm 0.4$ | $3.2 \pm 0.3$ | $3.1 \pm 0.3$ | $2.9 \pm 0.3$ |
| Data | 3 | 4 | 2 | 0 | 0 |

We check the prediction of our background sources with data in control regions where the background contribution is maximized. For the $\mu\mu$ analysis the region is defined by requiring two muons with $P_T > 25$ GeV/c, $75 < m_{\mu\mu} < 105$ GeV/c$^2$ and 2 jets with $E_T > 30,15$ GeV. We observe 110 events and expect $88 \pm 10$. For the $\mu\nu$ analysis we ask for one muon with $P_T > 25$ GeV/c,

$\not{E}_T > 35$ GeV and 2 jets with $E_T > 30$ GeV and observe 203 events to be compared with a prediction of $221 \pm 15$ from SM sources.

The efficiency to detect our signal is obtained from MC simulated LQ (PYTHIA) events to account for kinematical and geometrical acceptance. The total efficiencies for a LQ signal are reported in Table II.

TABLE II: Efficiencies after all cuts, errors (statistical and systematic) and 95% C.L. upper limits on the production cross section $\times$ branching fraction Br, as a function of $M_{LQ}$, for the two channels.

| $M_{LQ}$(GeV/c$^2$) | $\mu\mu jj$ | | $\mu\nu jj$ | |
|---|---|---|---|---|
| | $\epsilon$ | $\sigma \times$Br(pb) | $\epsilon$ | $\sigma \times$Br(pb) |
| 100 | $0.020 \pm 0.003$ | 1.35 | $0.0050 \pm 0.0005$ | - |
| 120 | $0.05 \pm 0.005$ | 0.52 | $0.070 \pm 0.005$ | 0.86 |
| 160 | $0.13 \pm 0.01$ | 0.18 | $0.070 \pm 0.005$ | 0.73 |
| 200 | $0.19 \pm 0.02$ | 0.13 | $0.110 \pm 0.005$ | 0.41 |
| 220 | $0.21 \pm 0.02$ | 0.11 | $0.13 \pm 0.01$ | 0.24 |
| 240 | $0.24 \pm 0.02$ | 0.10 | $0.13 \pm 0.01$ | 0.24 |
| 260 | $0.26 \pm 0.02$ | 0.09 | $0.14 \pm 0.01$ | 0.21 |

The following systematic uncertainties are considered

when calculating signal acceptance and background pre-

dictions: i) luminosity: 6% ii) choice of parton distribution functions: 2.1% iii) statistical error of MC < 1.2% iv) jet energy calibration scale < 1% v) muon reconstruction : 0.8% vi) $z_{vertex}$ cut : 0.5%. vii) initial and final state radiation 1.8%. After all selection cuts, 2 events remain in the $\mu\mu$ channel, while the number of events remaining in the $\mu\nu$ channel is reported in Table I.

In the analyses described above the number of events passing the selection cuts is consistent with the expected number of background events. The conclusion of the two searches is that there is no LQ signal: hence we derive

an upper limit on the LQ production cross section at 95% confidence level. We use a Bayesian approach[22] with a flat probability distribution for the signal cross section and Gaussian distributions for acceptance and background uncertainties. The cross section limits are tabulated in Table II and the mass limits are tabulated in Table III. To compare our experimental results with the theoretical expectation, we use the next-to-leading order (NLO) cross-section for scalar LQ pair production from [23] with CTEQ6 parton distribution functions[24].
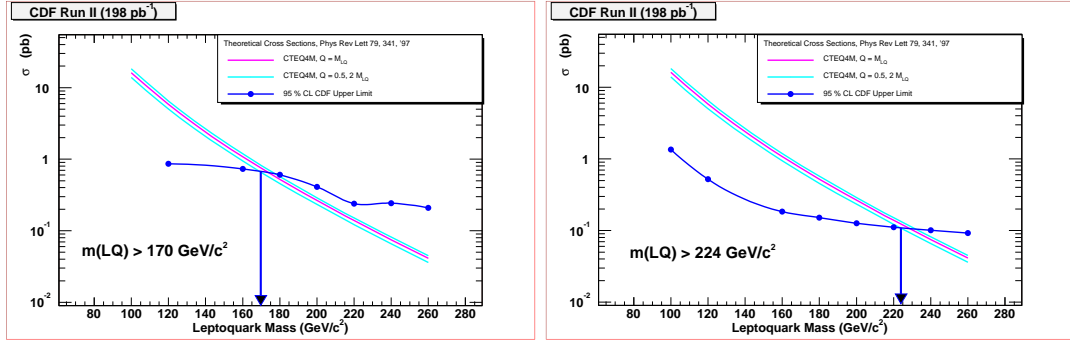


FIG. 3: 95% C.L. limit on the experimental cross section times branching ratio as a function of the LQ mass for the $\mu\nu jj$ and $\mu\mu jj$ channel. The NLO theoretical cross section is plotted for different values of the renormalization scale. Mass limits of 170 GeV/c$^2$ and 224 GeV/c$^2$ respectively are obtained.

The theoretical uncertainties correspond to the variations from $M_{LQ}/2$ to $2M_{LQ}$ of the renormalization scale $\mu$ used in the NLO QCD calculation. To set a limit on the LQ mass we compare our 95% CL upper experimental limit to the theoretical cross section for $\mu = 2M_{LQ}$, which is conservative as it corresponds to the lower value of the theoretical cross section. We find lower limits on M(LQ) at 224 GeV/c$^2$ ($\beta = 1$) and 170 GeV/c$^2$ ($\beta = 0.5$). They are reported in Figure 3. To obtain the best limit however, we combine the results from the two decay channels just described with the result of a search for LQ in the case where the LQ pair decays to a neutrino and quark with branching ratio $Br(LQ \rightarrow \nu q)$ =1.0[10]. The individual channel analyses are in fact optimized for fixed values of $\beta$ (1,0.5,0) while in the combined analysis, due to the contributions of the different decay channels, the signal acceptance can be naturally expressed as a function of $\beta$. As for the treatment of uncertainties, the searches in the $\mu\mu jj$ and $\mu\nu jj$ channels use common criteria and sometime apply the same kind of requirements so the uncertainties in the acceptances are considered correlated. When calculating the limit combination including the $\nu\nu jj$ channel the uncertainties are considered

uncorrelated. For each $\beta$ value a 95% C.L. upper limit on the expected number of events is returned for each mass, and by comparing this to the theoretical expectation, lower limits on the LQ mass are set. The combined limit as a function of $\beta$ is shown in Figure 4, together with the individual channel limits. The combined mass limits are also tabulated in Table III.

The final result presented here is better than the results obtained with Tevatron Run I data[5]. This is mostly due to the small increase in the cross section as a function of the center of mass energy (from 1.8 to 1.96 TeV), and an increase in the muon acceptance. A comment is in order when comparing this result with the ones recently published[7] for first generation LQ and third generation LQ[25]. While the signatures of LQ production is very similar (high $P_T$ leptons, large transverse missing energy and energetic jets) one has to consider the constraint on the LQ particle to only couple to same generation fermions. This implies different types of selection and exclude the possibility of combining inter-generation results. Also, in the case of electrons and muons, as can be seen from the current results, the similarity in their acceptance results in similar cross section and mass limits,

TABLE III: 95% C.L. lower limits on the second generation scalar LQ mass (in GeV/c$^2$), as a function of $\beta$. The limit from CDF[9] ($\mu\mu jj$) Run I ($\sim 120pb^{-1}$) is also given.

| $\beta$ | $\mu\mu$ jj | $\mu\nu jj$ | $\nu\nu jj$ | Combined | CDF Run I |
|---|---|---|---|---|---|
| 0.01 | - | - | 114 | 125 | - |
| 0.05 | - | - | 110 | 133 | - |
| 0.1 | - | 137 | - | 143 | - |
| 0.2 | - | 155 | - | 157 | - |
| 0.3 | 100 | 162 | - | 176 | - |
| 0.4 | 152 | 168 | - | 200 | - |
| 0.5 | 171 | 170 | - | 208 | - |
| 0.6 | 184 | 168 | - | 213 | - |
| 0.7 | 196 | 162 | - | 217 | - |
| 0.8 | 206 | 155 | - | 221 | - |
| 0.9 | 215 | 137 | - | 224 | - |
| 1.0 | 224 | - | - | 226 | 202 |
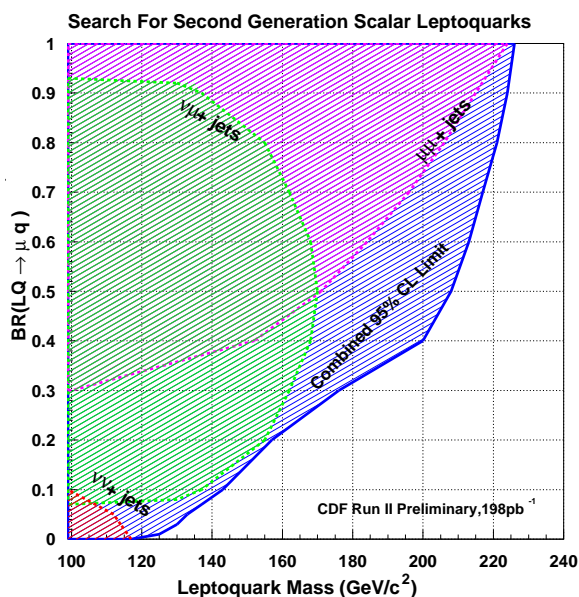


FIG. 4: Leptoquark mass exclusion regions at 95% C.L. as function of Br(LQ$\to \mu$ q).

while the result is quite different in the case of third generation LQ, due to the much smaller acceptance for $\tau$ leptons. The results presented in this paper, as well as the ones recently published in [7], are obtained with a statistical sample corresponding to about twice the luminosity collected in Tevatron Run I. A future increase in the Run II luminosity by an order of magnitude is estimated to extend the LQ mass range to $\sim 300$ GeV/c$^2$ for the $\beta$ = 1 case [26]. Substantially higher LQ masses will be explored at the future Large Hadron Collider (LHC)[27].

In conclusion, we have performed a search for pair production of second generation scalar LQ in the dimuons + jets and muon, missing energy + jets topologies, using 198 pb$^{-1}$ of proton-antiproton collision data recorded by the CDF experiment during Run II of the Tevatron.

We combined these findings with the ones from a search in the $\not{E}_T$ + jets topology[10]. No evidence for LQ is observed. Assuming that the LQ decays to muon and quark with variable branching ratio $\beta$ we exclude LQ with masses below 226 GeV/c$^2$ for $\beta = 1$, 208 GeV/c$^2$ for $\beta = 0.5$ and 143 GeV/c$^2$ for $\beta = 0.1$ at 95% C.L.

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